

# RECENT RESULTS FROM HEAVY ION COLLISIONS

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Systematic trends of baryon transport, chemical freeze-out, and kinetic freeze-out in high energy nuclear collisions are presented. Further measurements of particles with heavy flavors are proposed in order to shed light on collision dynamics at parton level.

## 1 Introduction

The purpose of the current heavy ion programs at CERN (Switzerland) and Brookhaven National Laboratory (USA) is to probe strongly interacting matter under extreme conditions, i.e. at high densities and temperatures. The central subject of these studies is the transition from the quark-gluon plasma to hadronic matter. In the early phases of ultra-relativistic heavy ion collisions, when a hot and dense region is formed in the center of the reaction, there is copious production of up, down, and strange quarks. Transverse expansion is driven by multiple scattering among the incoming and produced particles. As the medium expands and cools, the quarks/gluons combine to form the hadrons that are eventually observed.

In this paper, we will summarize the recent experimental results on transverse momentum distributions and particle ratios. The related physics issues are chemical equilibrium and collective expansion. While the former has to do with inelastic collisions, the later is dominated by the elastic cross section. We will focus at the relatively low transverse momentum region,  $p_t \leq 2$  GeV/c, where the bulk production occurs. Experimental results are from refs. [1-9] and for results on high momentum transfer, global measurements, and correlations readers are referred to ref. [10].

## 2 Baryonic Physics: mid-rapidity $\bar{p}/p$ ratios and inclusive net-proton distributions

All RHIC experiments have consistently measured the ratio of  $\bar{p}/p$  at mid-rapidity<sup>11,12,13,14</sup>. It is found that at mid-rapidity, the ratio is not unity and a dramatic increase in the ratio is observed from SPS to RHIC, meaning that the system created at  $\sqrt{s_{NN}} = 130$  GeV is not yet net-baryon free<sup>11</sup>.

One of the unsolved problems in high energy nuclear collisions is the

baryon transfer that occurs at the early stage of the collision<sup>15</sup>. The later dynamic evolution of the system is largely determined at this moment since the available energy is fixed at this stage of the collision. On the theoretical side, a novel mechanism, the non-perturbative gluon junction, was proposed to address this problem<sup>16,17</sup>. From the STAR measured  $\bar{p}/p$  ratios<sup>11</sup> and the STAR preliminary results of anti-proton yields<sup>18</sup>, we have extracted the net-proton yields at mid-rapidity. The values are shown in Fig. 1 as a function of collision centrality. No hyperon decay corrections have been applied as that requires the knowledge of the yields of hyperons.

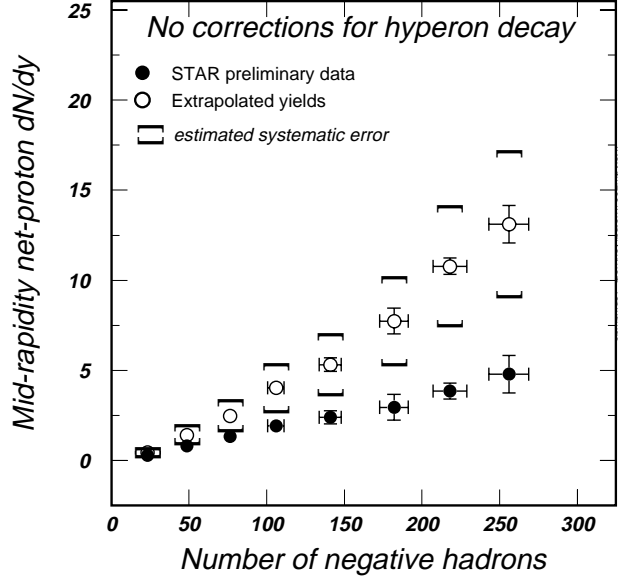


Figure 1. Inclusive net-protons yields vs. charge particle multiplicity. Open and filled symbols represent the yields within  $p_t \leq 1$  GeV/c and the values extracted from the full transverse momentum range, respectively.

One can see that the number of net-protons increases as the number of the negatively charged particles increases. This implies that more and more protons (baryons) are transferred from the incoming nuclei to mid-rapidity as the overlap of the two nuclei increases. More data are needed to study the role of the junction mechanism<sup>16,17</sup> in heavy ion collisions. In this respect, the rapidity distributions of the net-protons as a function of collision centrality will be of crucial importance.

### 3 Chemical Freeze-out: particle ratios

Recently, much theoretical effort has been devoted to the analysis of particle production within the framework of statistical models<sup>19,20,21</sup>. These approaches are applied to the results of both elementary collisions ( $e+e^-$ ,  $p+p$ ) and heavy ion collisions ( $Au+Au$  and  $Pb+Pb$ )<sup>19</sup>. Many features of the data imply that a large degree of chemical equilibration may be reached both at AGS and SPS energies. The three most important results are: (i) at high energy collisions the chemical freeze-out (inelastic collisions cease) occurs at about 160-180 MeV and it is ‘universal’ to both elementary and heavy ion collisions; (ii) the kinetic freeze-out (elastic scatterings cease) occurs at a lower temperature  $\sim 120-140$  MeV; (iii) the compilation of freeze-out parameters<sup>21</sup> in heavy ion collisions in the energy range from 1 - 200 A·GeV shows that a constant energy per particle  $\langle E \rangle / \langle N \rangle \sim 1$  GeV can reproduce the behavior in the temperature-potential ( $T_{ch} - \mu_B$ ) plane<sup>21</sup>.

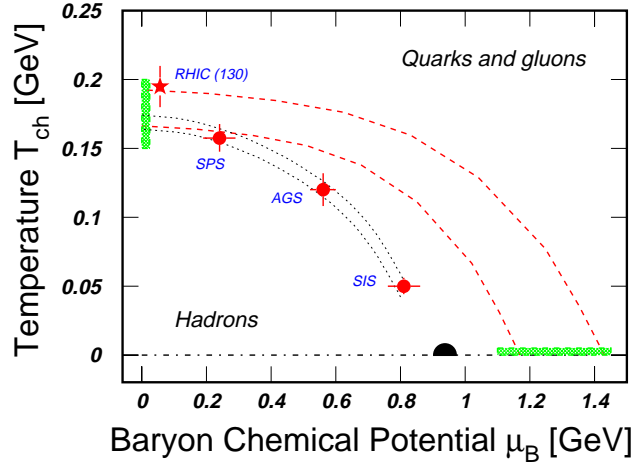


Figure 2. Phase plot  $T_{ch}$  vs.  $\mu_B$ . Dashed-line represents the boundary between interactions involving hadronic and partonic degrees of freedom. Dotted-lines represent the results of [21]. The ground state of nuclei is shown as half circle.

The systematics for chemical parameters is shown in the phase plot in Fig.2 where the dashed lines represent the boundary between interactions involving hadronic and partonic degrees of freedom. The dotted lines represent the results of ref. [21]. The lattice prediction on  $T_c$  ( $\approx 160$  MeV) is shown at  $\mu_B = 0$  and the baryon density for neutron stars is indicated at  $T_{ch} = 0$ .

#### 4 Kinetic Freeze-out: transverse momentum distributions

The measured transverse momentum distributions have been fitted by the exponential function  $f = A \cdot \exp(-m_t/T)$ , where  $T$  is the slope parameter and  $A$  is the normalization constant. The magnitude of the slope parameter provides information on temperature (random motion in local rest frame) and collective transverse flow. Fig. 3(a) shows the measured particle slope parameters from Pb+Pb central collisions at SPS ( $\sqrt{s_{NN}} = 8.8$  GeV and  $\sqrt{s_{NN}} = 17.2$  GeV) energies<sup>8,9,22,23</sup>. Recent results are:

- Particle distributions from 40 A· GeV ( $\sqrt{s_{NN}} = 8.8$  GeV) collisions were reported by NA45 and NA49<sup>8,9</sup>. The slope parameters are similar to the ones observed at 158A· GeV, *i.e.*, they follow the established systematic trend<sup>24</sup>;
- The systematic of the transverse momentum distributions for  $J/\psi$  was reported by the NA50 experiment<sup>6,7</sup>. It is interesting to note that the slope parameter of  $J/\psi$  is similar to those for  $\phi$  and  $\Omega$ ;
- For central collisions the  $\phi$  slope parameter of NA49 is about 300 MeV<sup>5</sup> whereas that of the NA50 is about 240 MeV. NA49 and NA50 reconstructed  $\phi$  mesons via  $K^+K^-$  and  $\mu^+\mu^-$  channels, respectively. As discussed in refs. [25,26], part of the difference may be caused by the final state interaction of the decay kaons. In fact, if one studies the centrality dependence of the  $\phi$  slope parameter, one finds that at peripheral collisions, both experimental results agree with each other and the value is close to that from  $p + p$  collisions<sup>5,6</sup>.

Preliminary results of the slope parameters from Au+Au central collisions at RHIC ( $\sqrt{s_{NN}} = 130$  GeV)<sup>4</sup> are shown in Fig. 3(b). It is obvious that the mass dependence of the slope parameter is stronger than that from collisions at SPS energies.

As one can see from Fig. 3(a), the slope parameters appear to fall into two groups: group (I) is flat as a function of particle mass, whereas the slopes in group (II) increase strongly with particle mass. At the RHIC energy, the slope parameter systematic of  $\pi$ ,  $K$ , and  $p$  shows an even stronger dependence on the particle mass. The strong energy dependence of the slope parameter might be the result of the larger pressure gradient at the RHIC energy. With a set of reasonable initial/freeze-out conditions and equation of state, the stronger transverse expansion at the RHIC energy was, in deed, predicted by hydrodynamic calculations<sup>27,28</sup>. In addition, the results are consistent with the large value of the event anisotropy parameter  $v_2$  at the RHIC energy<sup>29,30</sup>.

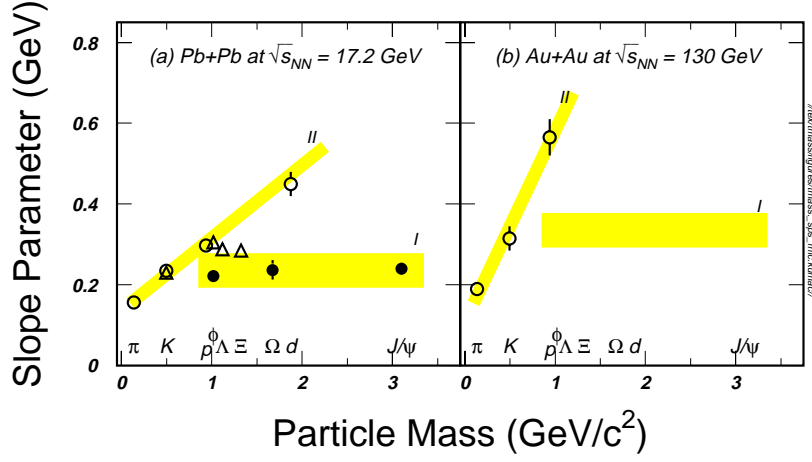


Figure 3. Slope parameters as a function of particle mass for (a) Pb+Pb central collisions at SPS ( $\sqrt{s_{NN}} = 17.2$  GeV) and Au+Au central collisions at (b) RHIC ( $\sqrt{s_{NN}} = 130$  GeV). Weakly and strongly interacting limits are indicated by I and II, respectively.

Within the hadronic gas, the interaction cross section for particles like  $\phi$ ,  $\Omega$ , and  $J/\psi$  are smaller than that of  $\pi$ ,  $K$ , and  $p$ <sup>31</sup>. Therefore the interactions between them and the rest of the system are weak, leading to the flat band behavior in Fig. 3(a). On the other hand, the slope parameter of these weakly interacting particles may reflect some characteristics of the system at hadronization. Then it should be sensitive to the strength of the color field<sup>32,33</sup>. Under this assumption, the fact that the weakly interacting particles show a flat slope parameter as a function of their mass would indicate that the *flow* develops at a later stage of the collision. Should the collective flow develop at the partonic level, one would expect to see a mass dependence of the slope parameters for all particles<sup>34</sup>.

Figure 4 shows the bombarding energy dependence of the freeze-out temperature  $T_{fo}$  and the average collective velocity  $\langle\beta_t\rangle$ . These parameters were extracted by hydrodynamic motivated model fitting<sup>35</sup>. It is interesting to observe that both  $T_{fo}$  and  $\langle\beta_t\rangle$  saturate at a beam energy of about 10 A·GeV. The saturation temperature is about 100 - 120 MeV, very close to the mass of the lightest meson<sup>36</sup>. The steep rise of the  $T_{fo}$  and  $\langle\beta_t\rangle$  up to about 5 A·GeV incident energy indicates that at low energy collisions the thermal energy es-

entially goes into kinetic degrees of freedom. The saturation at  $\sim 10$  A·GeV shows that particle generation becomes important. As proposed in<sup>36,37</sup>, for a pure hadronic scenario there may be a limiting temperature  $T_c \approx 140$  MeV in high-energy collisions, although the underlying physics for both, the transition from partonic to hadronic degrees of freedom and the transition from interacting hadrons to free-streaming is not clear at the moment. By coupling the limiting temperature idea to a hydrodynamic model calculation, Stöcker *et al.* successfully predicted<sup>38</sup> the energy dependence of the freeze-out temperature.

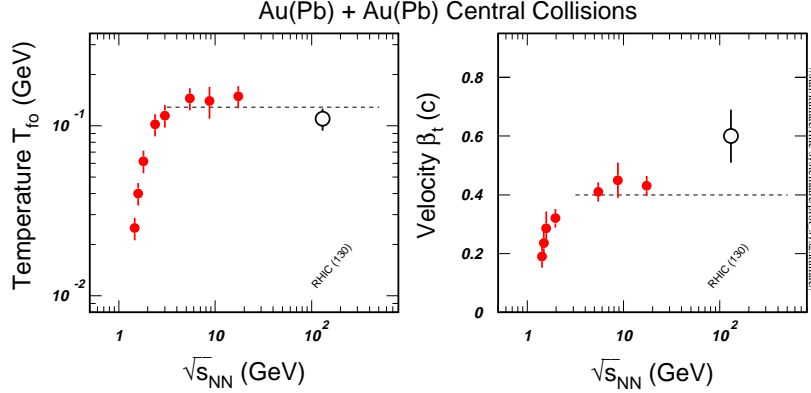


Figure 4. Systematics of kinetic freeze-out temperature parameter  $T_{fo}$  and average collective transverse flow velocity  $\langle\beta_t\rangle$  as a function of beam energy. At  $\sqrt{s_{NN}} \approx 5$  GeV, both values of temperature and velocity parameters seem to saturate. However, the velocity parameter extracted from central collisions at the RHIC energy is higher than values from collisions at lower beam energies.

At the RHIC energy, the collective velocity parameter seems to be larger than that from collisions at AGS/SPS energies. This can already be seen in Fig. 4 where the increase from pion to proton at  $\sqrt{s_{NN}} = 130$  GeV (Fig. 3(b)) is much faster than at  $\sqrt{s_{NN}} = 17$  GeV (Fig. 3(a)). Is this a manifestation of van Hove's<sup>39</sup> picture? On the other hand, compared to results from lower energy collisions, the temperature parameters seem to be lower. Is this the consequence of hydrodynamic expansion from a higher initial density fireball? An energy scan between  $\sqrt{s_{NN}} = 20 - 130$  GeV will be extremely important in order to study this evolution in more detail.

## 5 Summary

In summary, the most interesting results from collisions at RHIC are that the system is indeed approaching net-baryon free and the transverse expansion is found to be stronger than that from collisions at AGS/SPS energies.

In order to understand the trend of the collective velocity, an energy scan between  $\sqrt{s_{NN}} = 20 - 200$  GeV, is important. In addition, systematic studies on the anisotropy parameter  $v_2$  and the transverse momentum distributions of  $\phi, \Omega$ , and  $J/\psi$  are necessary as they will help in determining whether the collectivity is developed at the partonic stage.

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